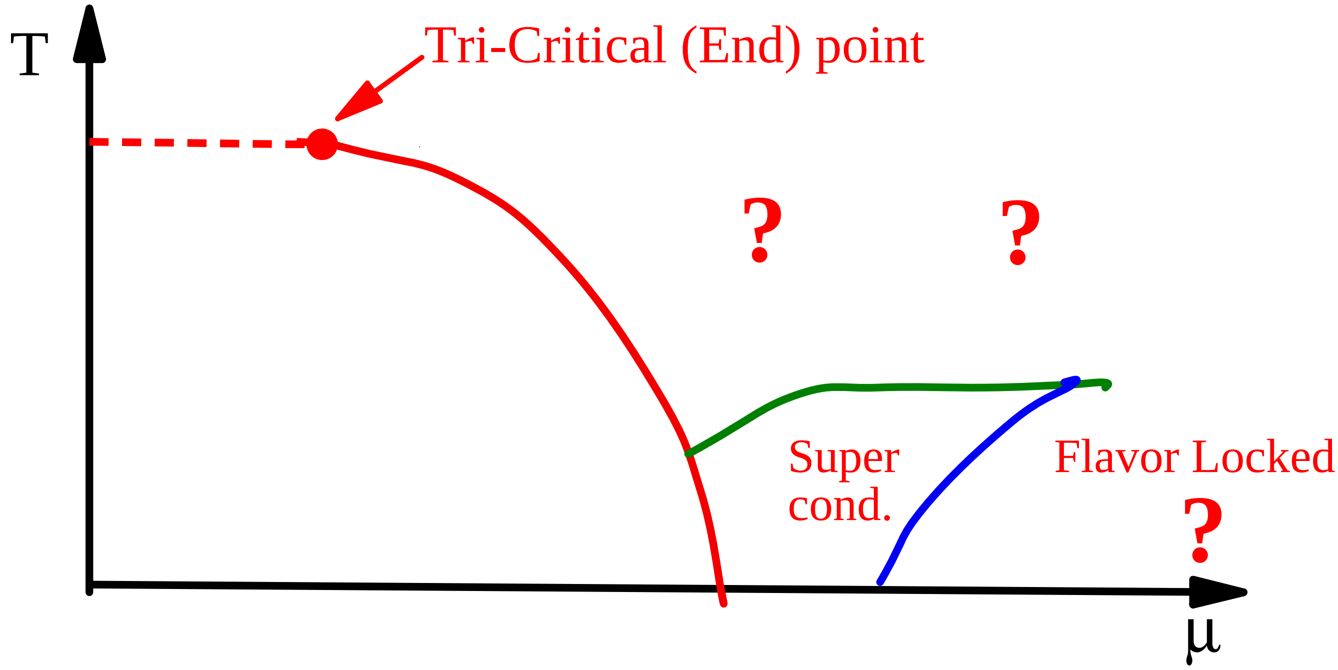
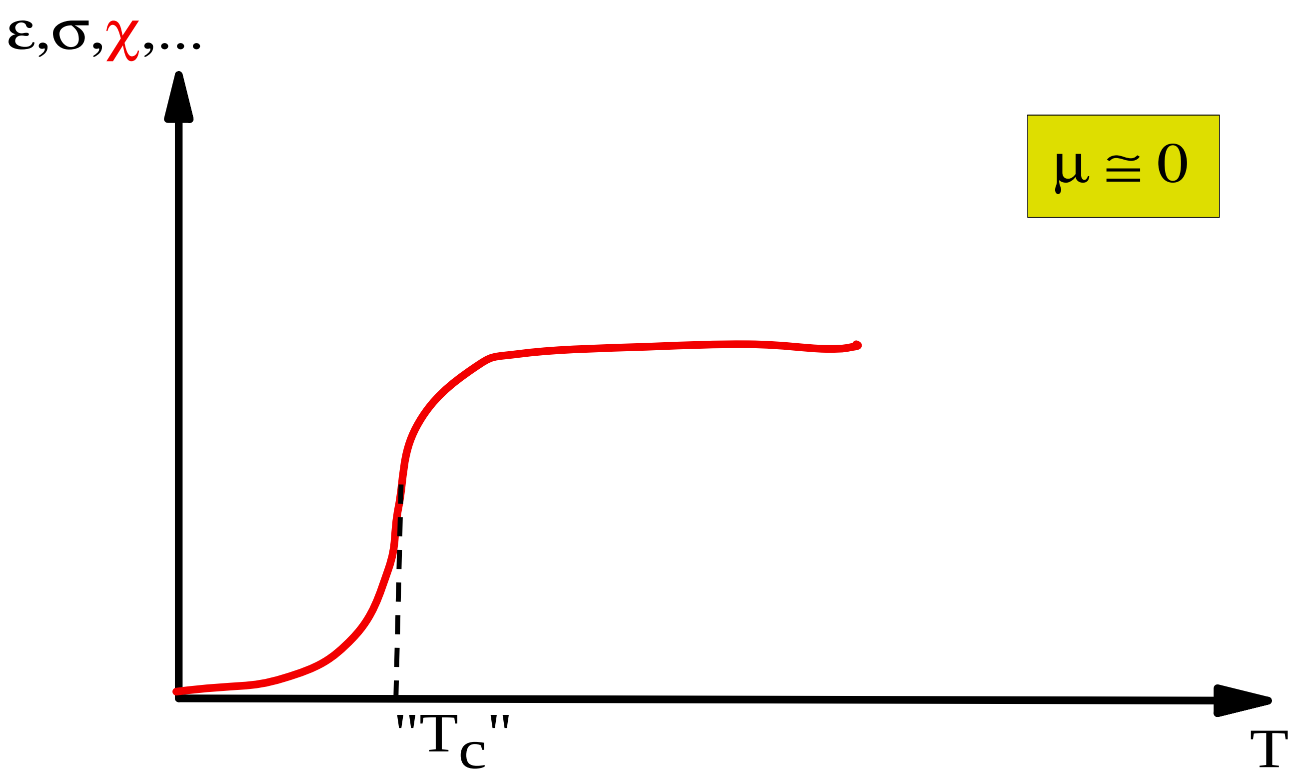
Event by Event fluctuations and the QGP

- Introduction and general discussion
- What can be addressed with E-by-E fluctuations
- Fluctuations of particle ratios
  - Charge fluctuations!
  - Fluctuations of conserved quantities
- Outlook

The QCD Phase-Diagram





Event-by-event fluctuations

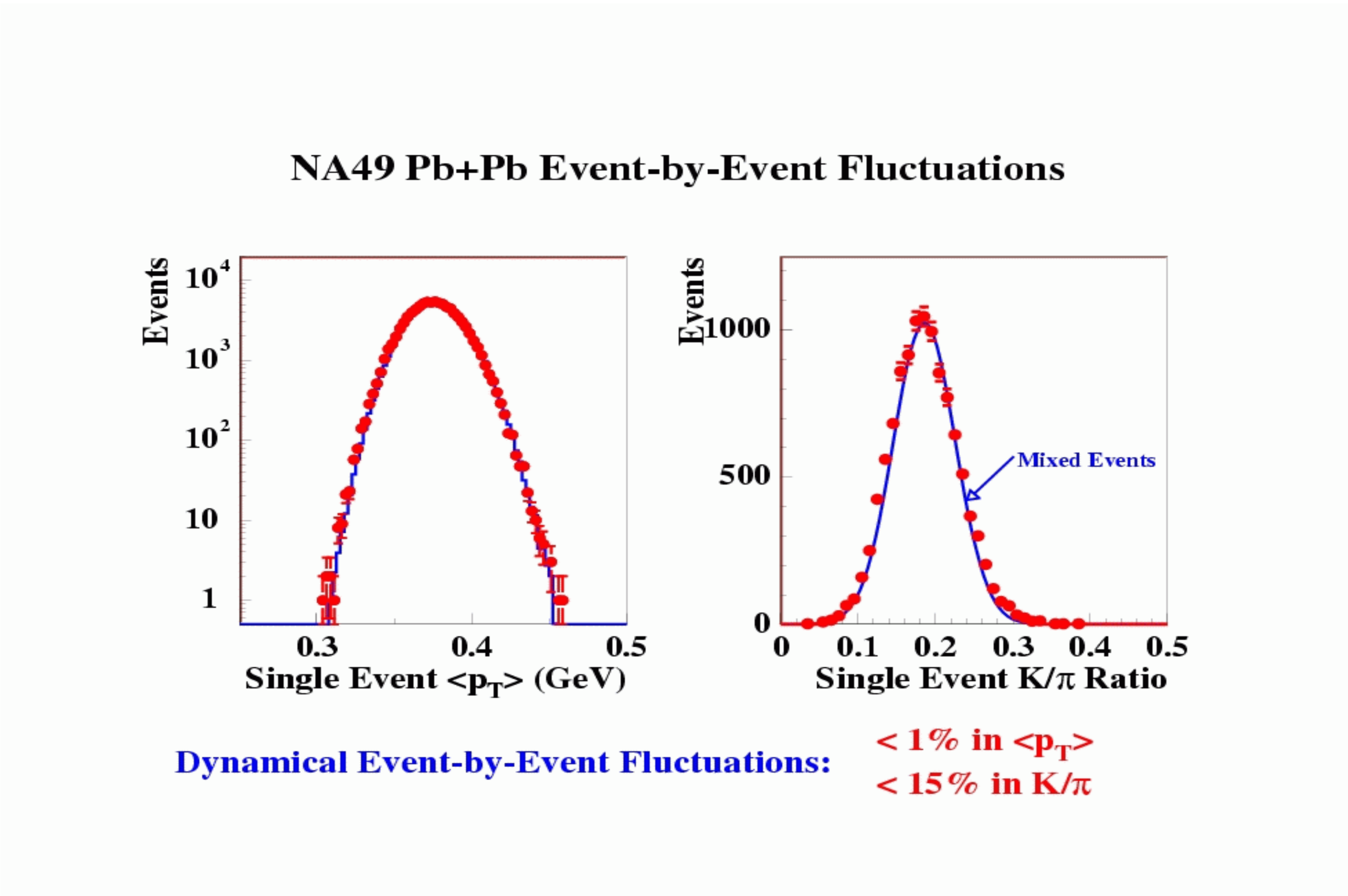
The old idea: Two distinct event classes

After the first experiments (NA49): GAUSSIANS, GAUSSIANS....

Physics is in the width of the Gaussian:

Event-by-Event

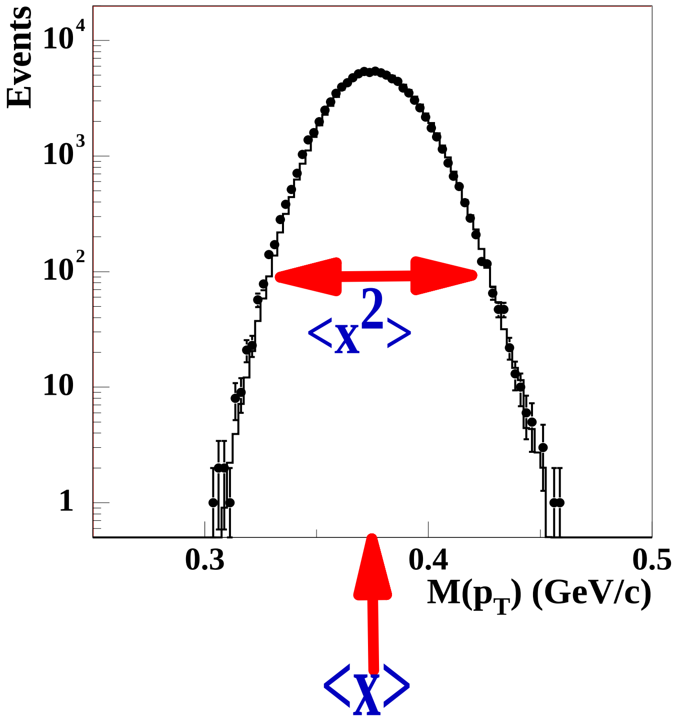
- First possibilities with NA49 and STAR
- first data from NA49
  $\Rightarrow$ Gaussians, with almost ($\pm$2%) statistical width!
- Theory is just now developing



E-by-E activities

- Temperature fluctuations (Stodolsky (95), Shuryak (98))
- "Phi"-messure (Gazdzicki,Mrowczynski(92))
- Quantum statistics (Mrowczynski (98))
- Two-particle correlations (Bialas, VK(99),Belkacem et al (99))
- Particle Ratios (Baym,Heiselberg(99), Jeon, VK (99,00))
- Resonance gas (Rajagopal,Shuryak,Stephanov (99), Jeon,VK (99))
- Phase transitions, bubble formation (Baym,Heiselberg (99), Rajagopal, Shuryak, Stephanov (99),Heiselberg, Jackson(00))
- charge fluctuations (Asakawa,Heinz Mueller(00), Jeon,VK(00),Dumitru,Pisarski(00), Stephanov,Shuryak(00))
- balance functions (Bass, Danielewicz,Pratt (00))
- Baryon number fluctuations(Asakawa,Heinz,Mueller(00), Gavin(00))
- Review article: Heiselberg, nucl-th/000304
- ....

Gaussians it is!



The physics is in the width!

For Gaussian shape, E-by-E measures 2-particle-correlations
(A. Bialas, VK, PLB 456 (99) 1)

$\Rightarrow$ Two arm spectrometer is sufficient

requires event-by-event

two-arm spectrometer is enough

Fluctuations (Widths)

measure generalized susceptibilities

$$\chi_{a,b} = \frac{dF}{da\ db}$$

Examples:

- Heat capacity $\Leftrightarrow$ T (or p_t) - fluctuations
- Baryon number susceptibility
  $\Leftrightarrow$ baryon number fluctuations
- charge susceptibility
  $\Leftrightarrow$ charge fluctuations

These susceptibilities can be calculated by Lattice QCD

Volume fluctuations

Even for the tightest trigger conditions, the volume created in and HI-collision fluctuates !

Typical observable:

$$\hat{O} = \rho V$$

Thus the fluctuations of O are "contaminated" by volume fluctuations

$$\delta\hat{O} = (\delta\rho)V + \rho\delta V$$

The physics is in $(\delta\rho)$!!!!

$\Rightarrow$ Study intensive (volume independent) quantities

- Particle Ratios $\Leftarrow$ this talk
- mean transverse momentum
- ...

Fluctuations of Particle Ratios

$$R = \frac{N_1}{N_2}$$

Correlations!!!

$$\begin{aligned}
\frac{\langle (\delta R)^2 \rangle}{\langle R \rangle^2} &= \langle \left(\frac{\delta N_1}{\langle N_1 \rangle} - \frac{\delta N_2}{\langle N_2 \rangle} \right)^2 \rangle \\
&= \left(\frac{\langle (\delta N_1)^2 \rangle}{\langle N_1 \rangle^2} + \frac{\langle (\delta N_2)^2 \rangle}{\langle N_2 \rangle^2} - 2 \frac{\langle \delta N_1 \, \delta N_2 \rangle}{\langle N_1 \rangle \, \langle N_2 \rangle} \right) \\
&= \left(\frac{\omega_1}{\langle N_1 \rangle} + \frac{\omega_2}{\langle N_2 \rangle} - 2 \frac{\langle \delta N_1 \, \delta N_2 \rangle}{\langle N_1 \rangle \, \langle N_2 \rangle} \right)
\end{aligned}$$

$$\langle (\delta N)^2 \rangle = \omega N$$

For poisson statistics (ideal gas): $\omega = 1$

$$\left.\begin{array}{ll} \text{Bose statistics:} & \omega > 1 \\ \text{Fermions} & \omega < 1 \end{array}\right\} \text{small corrections}$$

NO Volume Fluctuations !!!

$$\frac{\delta N_1}{\langle N_1\rangle} - \frac{\delta N_2}{\langle N_2\rangle} = \frac{\delta\rho_1 V + \rho_1\delta V}{\rho_1 V} - \frac{\delta\rho_2 V + \rho_2\delta V}{\rho_2 V}$$
$$= \frac{\delta\rho_1}{\rho_1} - \frac{\delta\rho_2}{\rho_2}$$

For $N_2 << N_1$ (such as K/π ratio)

$$\frac{<(\delta R)^2>}{<R>^2} \cong \frac{\omega_2}{<N_2>}$$

⇒ "simple" statistics dominated by the fluctuations of the smaller number

⇒ NA49 results for K/π ratio!

Look at $N_1 \approx N_2$ in order to find correlations

Fluctuations of π^+/π^-

(with S. Jeon, PRL83 (1999) 5435)

Consider fluctuations of $R = \frac{\pi^+}{\pi^-}$

$$\frac{<(\delta R)^2>}{<R^2>} = \left(\frac{<(\delta\pi^+)^2>}{<\pi^+>^2} + \frac{<(\delta\pi^-)^2>}{<\pi^->^2} - 2\frac{<\pi^+\pi^-> - <\pi^+><\pi^->}{<\pi^+><\pi^->} \right)$$

Correlation term

- No contribution from volume fluctuations
- $\rho^0 \rightarrow \pi^+ \pi^-$, $\omega \rightarrow \pi^+ \pi^- \pi^0$ reduce fluctuations

Sensitive to number of rho and omega at hadronization!!!!

Predict: For thermal weights fluctuations should be only 70 % of statistical.

Find: Deviations from statistical fluctuation are very sensitive to rho and omega at ***hadronization***
$\Leftrightarrow$ Dilepton Production

Fluctuations of H^+ / H^-

(with S. Jeon, PRL85 (00) 2076)

Consider: $R = \frac{N^+}{N^-} = \frac{1+F}{1-F}$ $F = \frac{N^+ - N^-}{N^+ + N^-} = \frac{Q}{N_{ch}}$

$Q = N_+ - N_-$ $N_{ch} = N_+ + N_-$

Net charge

$$<(\delta R)^2> = 4<(\delta F)^2> \cong 4\frac{<(\delta Q)^2>}{<N_{ch}>^2}$$

Propose Observable:

$$<N_{ch}><(\delta R)^2> \cong 4\frac{<(\delta Q)^2>}{<N_{ch}>} \propto \frac{\chi}{\sigma}$$

$$\left.\begin{array}{ll} \chi = -\frac{\partial^2 \phi}{\partial \mu_Q^2} & \text{Charge-Susceptibility} \\ \\ \sigma & \text{Entropy-density} \end{array}\right\} \text{Lattice}$$

Fluctuations in H^+ / H^-

Quark Gluon Plasma:

$$\frac{<(\delta Q)^2>}{<N_{ch}>} \propto \frac{<(\delta Q)^2>}{S} \frac{S}{<N_{ch}>} = \frac{Q_u^2 N_u + Q_d^2 N_d}{4(N_u + N_d + N_g)} \frac{S}{<N_{ch}>}$$

$$\boxed{N_{ch} <(\delta R)^2> \approx 1-1.4}$$

Pion Gas:

$$\frac{<(\delta Q)^2>}{<N_{ch}>} = \frac{1^2 <N_{\pi^-}> + 1^2 <N_{\pi^+}>}{(<N_{\pi^+}> + <N_{\pi^-}>)}$$

$$\boxed{<N_{ch}><(\delta R)^2> = 4}$$

Hadron gas, incl. resonances (~30% reduction of $<(\delta R)^2>$)

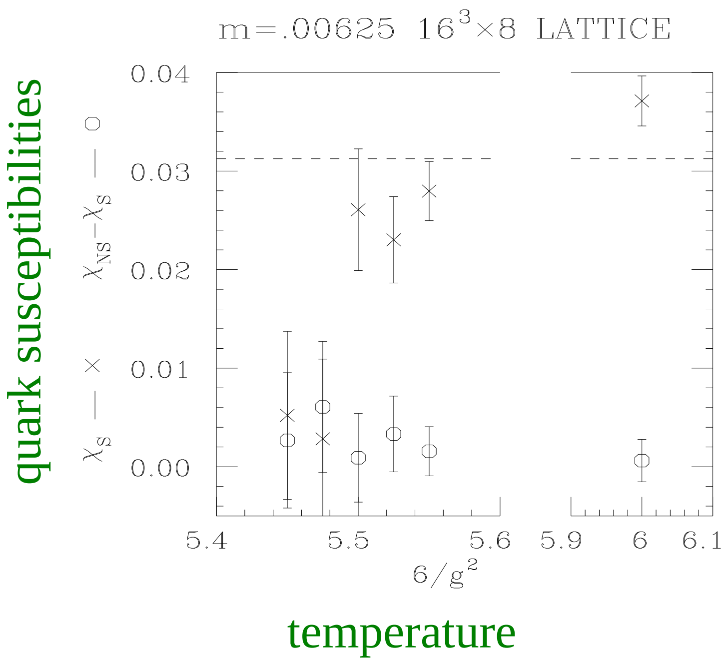
$$\boxed{<N_{ch}><(\delta R)^2> \cong 3}$$

Observable changes by Factor ~ 2-3 if phase transition

Reminder of: $$R_{e^+e^-} \equiv \frac{e^+e^- \to \text{Hadrons}}{e^+e^- \to \mu^+\mu^-} = N_c \sum_q Q_q^2$$

Lattice Results

(Gottlieb et al, PRD55(97) 6852)



Findings: $<\delta N_u \delta N_d> \approx 0;$

$<\delta N_f^2> \approx <N_f>$

$<S_{gluon}> \approx 3.6 <N_{gluon}>$

$<S_{quarks}> \approx (1/2) \times 4.2 <N_{quarks}>$

Simple estimate for $(<\delta Q^2>/S)$ agrees well with present Lattice results

Fluctuations of conserved quantities

Asakawa, Heinz, Mueller, PRL85 (00) 2072

S. Jeon and V.K. PRL85 (00) 2076

General idea: Given strong longitudinal expansion
the fluctuations of conserved quantities
will be preserved during hadronization
and hadronic phase

Requirements: Equilibration and buildup of
longitudinal flow in partonic phase

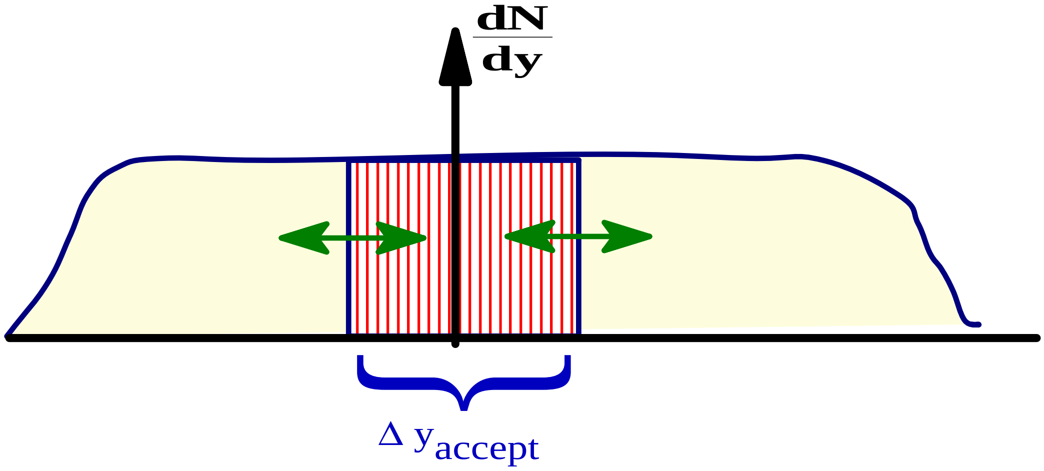
This is NOT an adiabatic transition through T_c

Examples:
- charge (this talk)
- baryon number (neutrons??)
- strangeness

Caution: These are extensive quantities
$\Rightarrow$ need to construct intensive quantity
such as N^+/N^- - ratio

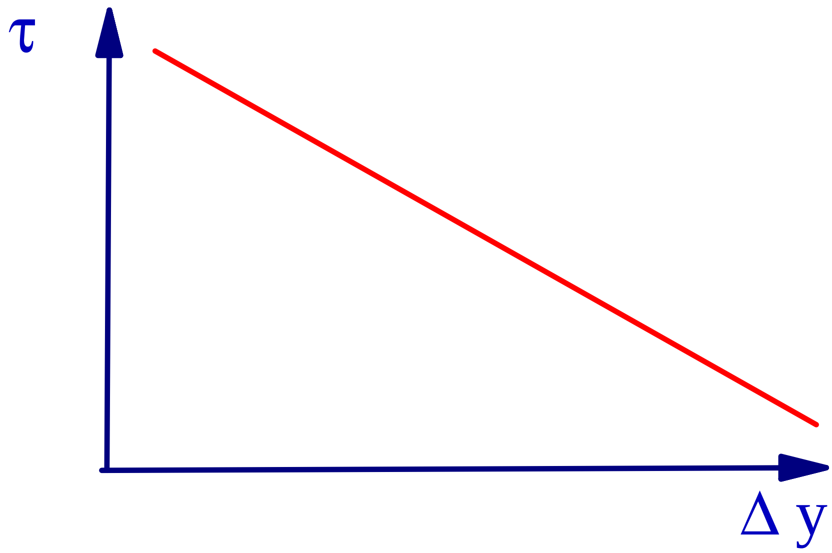
Rescattering

(hadronization)

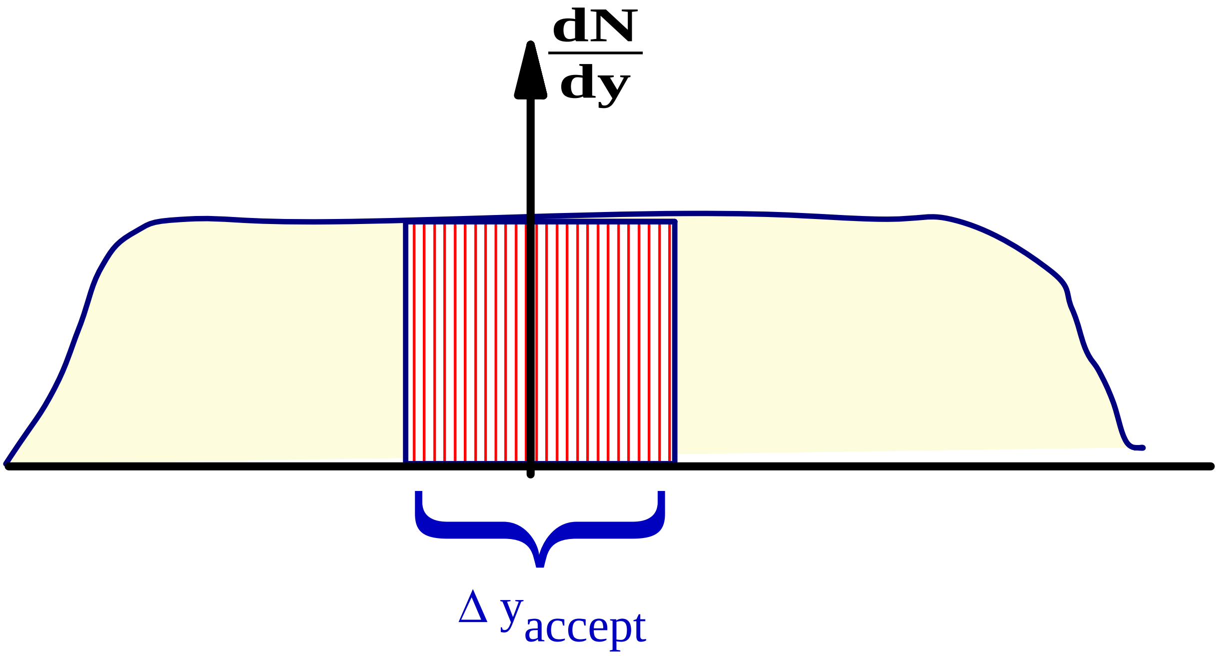


If: $\Delta y_{accept} >> \Delta y_{collision} \Rightarrow$ negligible

General trend: The larger Δ y the deeper one looks into the event



Acceptance



For Δy_{accept} << Δy_{total} $\Rightarrow$ grand canonical ensemble for $<\delta Q^2>$

Correction for charge conservation: $$F_Q = \left(1 - \frac{<N_{ch}>_{\Delta y}}{<N_{ch}>_{total}}\right)$$

In Bjorken picture:

Within Δy_{accept} $\begin{cases} \text{charge is conserved} \\ S_{initial} \leq S_{final} \end{cases}$

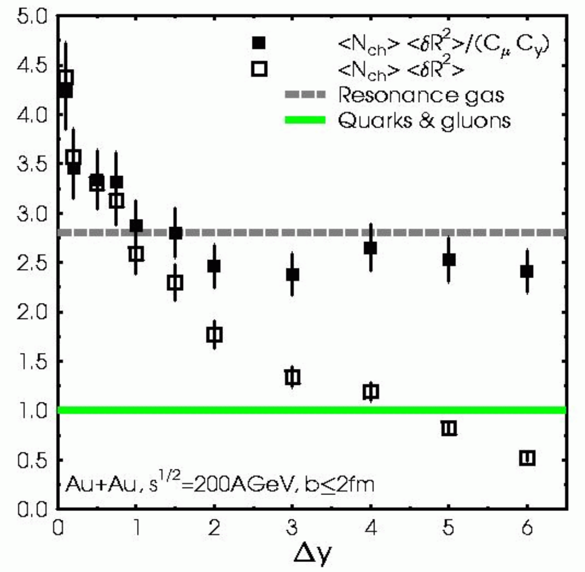
$$\Rightarrow \boxed{\left.\frac{<(\delta Q)^2>}{S}\right|_{final} \leq \left.\frac{<(\delta Q)^2>}{S}\right|_{initial}}$$

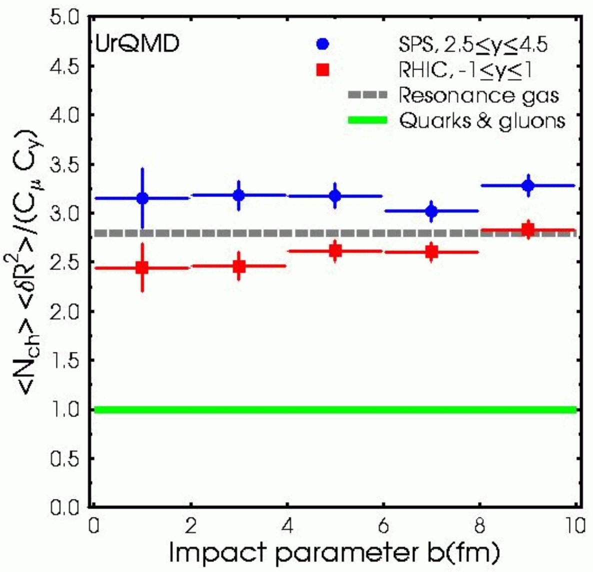
Transport results

(URQMD)

(M. Bleicher, S. Jeon and V.K. PRC62 (00) 061902)

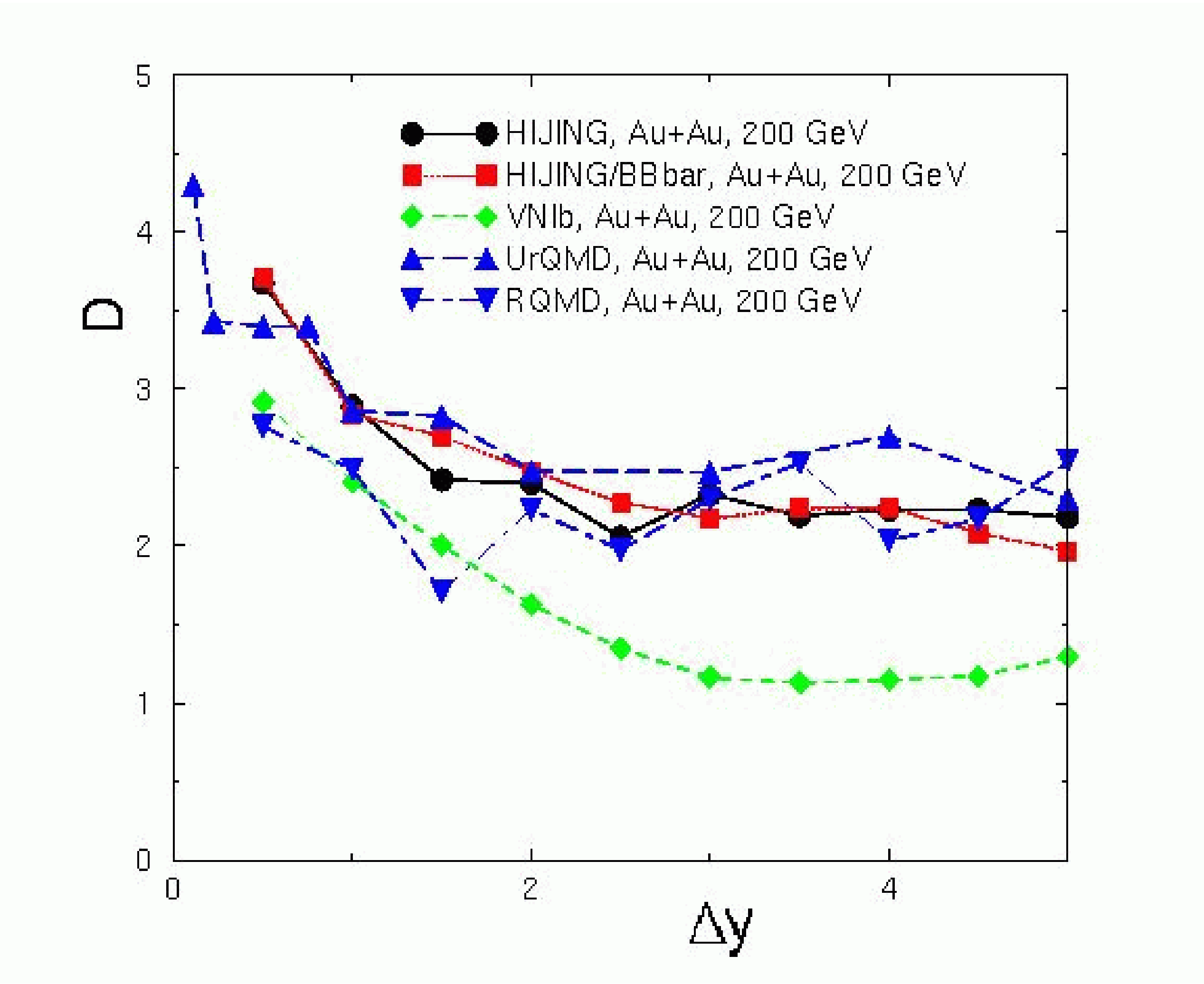
- Acceptance corrections essential
- works for wide range of b and y
- URQMD consistent with prediction for Hadron Gas
- $\Delta y > 1$ to capture resonances





Transport results Comparison

(C.Gale, V. Topor Pop and Q.H. Zhang)



Caveats

- Hadronization (Parton cascade....)
- Resonances? (NO!)
- Finite acceptance corrections (solved)
- Rescattering in hadronic phase (not an issue, choose Δy sufficiently large $\Rightarrow$LHC)
- Mixture of QGP and HG (always a problem)
- proton-proton (same as HG, lots of data in the '70)
- ....

Rescattering

(some numbers)

More detailed discussion based on diffusion eq:
(Shuryak and Stephanov, hep-ph/0010100)

$$<(\delta Q)^2> = <(\delta Q)^2>_{equil.} F(x) \; + \; <(\delta Q)^2>_0 \, (1 - F(x))$$

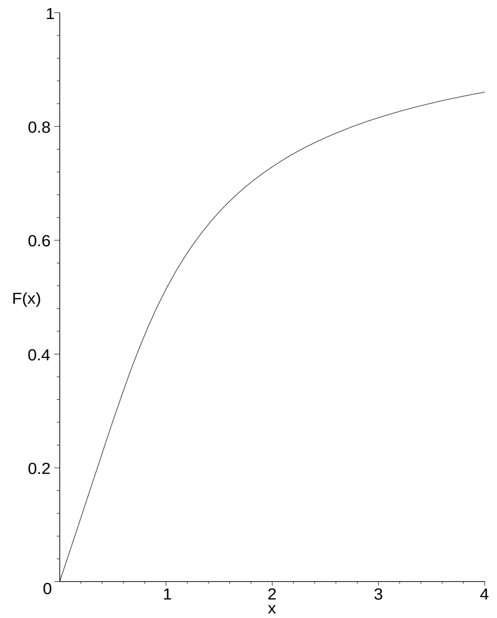
$$x = \frac{\Delta y_{diff}}{(\Delta y_{accept}/2)} \qquad (\Delta y_{diff})^2 = \int_0^\tau (y_{coll})^2 \frac{d\tau}{\tau_{free}}$$

Hadronic transport (Δy=4):

$y_{coll} \approx 0.8, \;\; \Delta y_{diff} \approx 0.6$

$\Rightarrow$ x $\approx$ 0.6
$\Rightarrow$ F(x) =0.34

$$\frac{<(\delta Q)^2>}{<(\delta Q)^2>_{equil.}} = 0.65$$



30% correction

Experimental issues

Detectors do fluctuate as well!

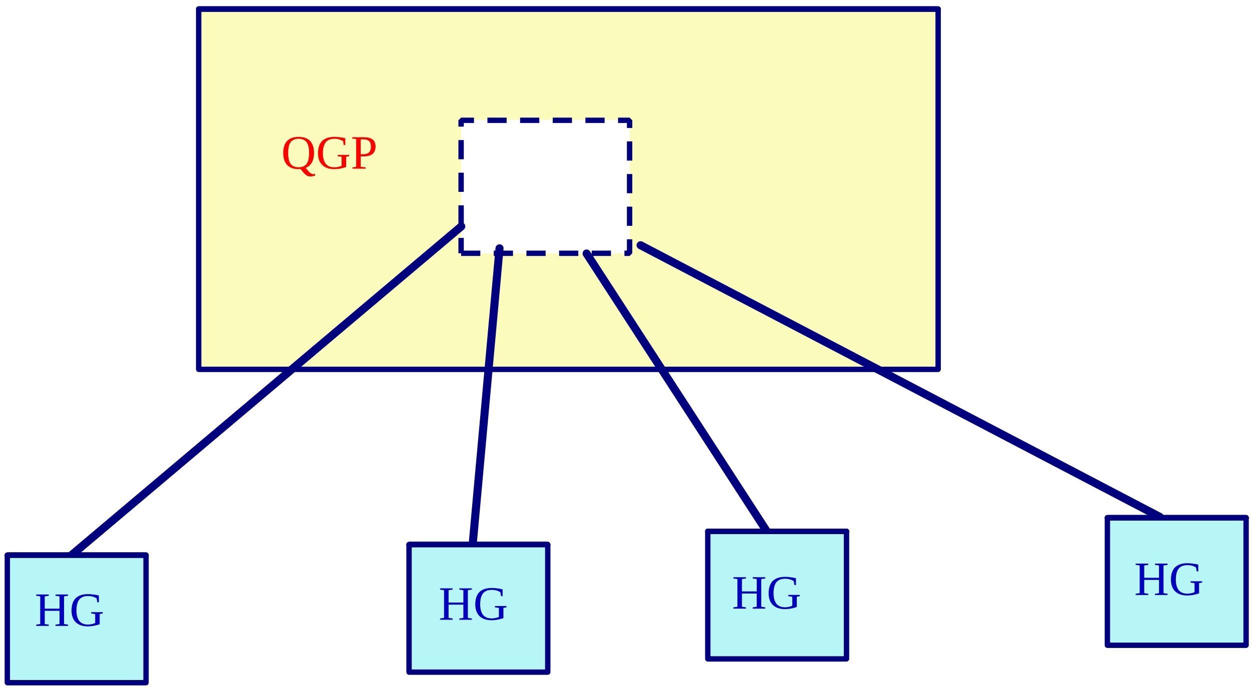
$$<\delta Q^2>_{measured} = <\delta Q^2>_{real} + \Delta^2(\text{detector})$$

example: $N = 1000$

$$\Rightarrow <\delta N^2>/N \approx 3\%$$

efficiency fluctuations ....

Speculate



Problem: Ensemble of HG-boxes should carry the same fluctuations per (entropy/energy) as QGP.
THIS is not a HG in chemical equilibrium

One way out (which at least does not violate obvious symmetries):

Enhance I=0 mesons, such as omega, eta ...

Simple estimate: ω up by factor ~5 $\Rightarrow$ PHENIX

Conclusions

- E-by-E measures particle correlations!
- Look at intensive variables to avoid Volume fluctuations
- Ratio fluctuations! (***NOT*** Ratios of Fluctuations)
- π^+/π^-: chemical equilibrium
- N^+/N^- : QGP-test
  - $\langle N_{ch}\rangle\langle(\delta R)^2\rangle \approx 3$ for hadron gas
  - $\langle N_{ch}\rangle\langle(\delta R)^2\rangle \approx 1$ for QGP
- Other applications: such as
  - K+/K- etc....
  - tri-critical point (lots of σ-mesons)
  - multifragmentaion
  - ...
- Waiting for the Data....

Absence of evidence is not evidence of absence

Conclusions (contd.)